Analyzing the impact of demand response and reserves in islands energy planning

Daniele Groppi [a,*], Felipe Feijoo [b], Antun Pfeifer [c], Davide Astiaso Garcia [a,d], Neven Duic [c]

[a] Department Department of Economics, Engineering, Society and Business Organisation (DEIM), University of Tuscia, Italy
[b] School of Industrial Engineering, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile
[c] Faculty of Mechanical Engineering and Naval Architecture University of Zagreb, Croatia
[d] Department of Planning, Design and Technology of Architecture Sapienza University of Rome, Italy

ARTICLE INFO

Handling Editor: Henrik Lund

Keywords:
Energy modelling
Energy planning
H2RES
Island flexibility
Smart energy island
Ancillary services

ABSTRACT

Small Islands usually rely on fossil fuels for their energy supply and face common challenges such as high energy costs and carbon dioxide emissions. For these reasons they represent interesting cases for analysing the transition towards a clean and secure energy system. Nevertheless, integrating non-dispatchable Renewable Energy Sources in the power grid causes stability issues and this is particularly true for island grids. Such issue is not fully considered in long-term energy planning; indeed, an important factor that should be considered in order to ensure the reliability of the grid are Reserves. There are different types of Reserves depending on the reactiveness/response time and the duration of the service. In this paper, primary and secondary reserves have been analysed in order to plan the long-term energy transition of the small island of Favignana, Italy by means of the new version of H2RES, a Linear Programming single-objective optimisation model able to provide a long-term capacity investment and dispatching optimisation. It has been found that biomass generators are favoured to both photovoltaic and wind turbines for their ability to provide reserves and also decrease the unpredictability of the supply. Batteries and Electrolysers are also used mostly for reserve provision.

1. Introduction

Even though the World economy is facing a global crisis [1], the process towards a decarbonised energy system is steadily proceeding [2]. Clean technologies investment are increasing and as such the share of renewable energy sources (RES) is increasing too [3]. European Countries have decided to invest heavily on renewables and are committed to be the first ones to reach carbon-neutrality [4] even more so after the recent energy crisis due to a sudden increase of fossil fuels prices [5], especially gas in the case of Europe [6], but this was also the case of coal that hit the economies of India and China [7]. The unexpected increase in fossil fuels cost, as well as the realisation of the vulnerability caused by energy dependence to foreign nations, has had the same effect that Carbon taxation might have had thus boosting even more investments in RES technologies [8] and the shift to a new age of clean technology manufacturing [9].

In this situation, islands offer an ideal environment to test innovative strategies aiming at providing essential clues and insights for the scalability and replicability of such solutions [10]. This is particularly true in the case of small islands, that most times have power grids strongly reliant on fossil fuels [11] that due to low systems inertia and stability issues [12] lead to energy costs much higher than those on the mainland [13] as well as extremely high greenhouse gas (GHG) emissions [14]. Moreover, small islands also suffer from the smaller opportunities for geographical diversification of sources thus all plants installed on the island suffer the same weather conditions thus representing a bigger threat to the power grid whenever a sudden change happens [15]. Also, Italy follows such idea, indeed a specific Ministerial Decree has been issued in order to establish the RES share that each small island not connected to the national grid must reach until 2030 [16].

One of the approaches to decarbonise small islands energy systems while ensuring their stability and safety is that of Smart Energy Systems (SESs) [17] and sector coupling [18]. Indeed, SES approach provides innovative and effective strategies to handle non-dispatchable RES power production [19]. Furthermore, SES also enables to decarbonise

* Corresponding author.
E-mail addresses: daniele.groppi@unitus.it (D. Groppi), felipe.feijoo@pucv.cl (F. Feijoo), antun.pfeifer@fsb.hr (A. Pfeifer), davide.astiasogarcia@uniroma1.it (D.A. Garcia), neven.duic@fsb.hr (N. Duic).

https://doi.org/10.1016/j.energy.2023.127716

other energy consuming sectors than the power one while optimally exploiting the synergies between all sectors and energy vectors [20] by means of different technologies and strategies such as demand response [21]. Several studies have proven such approach focusing on generic demand response programmes [22], on the interaction between different storage and RES technologies [23] on the connection with the transportation sector [24] or the residential heating one [25], on the benefits of district heating and cooling networks [26]. Moreover, the approach has also been tested at different scales, from the single building scale [27] to the national [28] and even continental one [29].

It is clear how such an integrated system requires complex analysis and careful energy planning so as to consider all sectors needs and necessities so as to ensure a just and efficient energy transition [30].

One of the best tool to do it is through energy system modelling and particularly via optimisation models, which have been proved to be a valuable tool for policy makers in this process.

Nevertheless, the difficulty in modelling such complex systems is evident. Conventional models usually adopt a simplified approach through low temporal and operational detail [31] but it has been proven how the increasingly high penetration of variable RES makes short-term system operation more important to consider even for long-term system planning [32]. To this extent, Palmintier [33] and Poncelet [34] analysed the impact of different constraints on results and they both came to the conclusion that operating reserve requirements has an important role. Additionally, Palmintier and Webster [35,36] concluded that neglecting some of these constraints has a significant impact on the obtained optimal results in terms of capacity and generation mix. Particularly, it results in low investments in flexible generators, which leads to reserve shortage, load shedding and additional renewable curtailment [37] as well as lower investments in flexible peak-load technologies and an underestimation of the total system costs [38]. Thus, an increasing number of studies have started to incorporate flexibility and stability constraints in long-term energy planning [39]. Recent studies can be found regarding the potential of EV as reserves providers and how different strategies can impact the energy system and the reserves [40].

The most advanced approach to consider such issues is that of considering ancillary reserves, an approach that is not found very often. Particularly, most models tend to consider this aspect through a Mixed-Integer Linear Programming (MILP) method [41] while very few models managed to maintain the model linear. An example can be given with the ReEDS model developed by NREL [42].

All these aspects gain even more importance in insular energy systems. Thus, the novelty of this paper is that of developing a linear constraints (representation) to include both primary and secondary reserves in a long-term energy planning model in order to assess the impact that considering stability issues might create to plan the future energy systems of small islands. The paper will focus on identifying the impact that considering, or not, such reserves has on the final results on the entire system as well as on single technologies operation in order to identify those technologies that best fit the role of flexibility providers. The analysis will be developed on the case study of the Favignana island as representative of the many not interconnected small islands in the Mediterranean as well as all others in mild-to-warm climates.

2. Methods

This section describes the main characteristics of the H2RES model [43]. What differentiate this model from others is the fact that it is a long-term model that considers sector coupling solutions while maintaining a high temporal (i.e. hourly) and technological resolution. H2RES is an optimisation model based on LP [44].

Fig. 1 shows the connections and interactions between the main sectors that are considered within the model that are the power, heat, industry and transport sectors.

The model is able to consider a great number of technologies, from the traditional generators to renewables such as solar, wind, and hydro-river (HROR).

The connection with the heating sector is enabled through Electric Boilers (EBs), Heat Pumps (HPs) or Combined Heat and Power (CHP) plants while, of course, also conventional boilers can cover such demand using different fuels. Additionally, H2RES has the ability to model different technologies within the same group of EBs or HPs thus allowing to consider several technologies within the same type, but with different technical parameters, capacity and costs (e.g., air-to-air, air-to-water, or ground source heat pump).

Furthermore, H2RES also takes into account the hydrogen (H_2) demand with an hourly resolution. The H_2 demand can also be distributed across different sectors (e.g. transport, building, industry) or can be considered as an overall H_2 demand (this can also consider the export of hydrogen). Moreover, the model also optimizes the size of electrolyzer (ELY) and H_2 storage in order to optimally cover such demands. Regarding the connection with the power grid, H2RES also analyses and optimize the size and dispatch of fuel cells (FC). As in the case of the heat sector, H2RES enables the user to consider several ELYs and FCs technologies, with distinct technical and economic parameters so as to compare different technologies and understand pros and cons of each one within the analysed timeframe.

As aforementioned, H2RES is a large-scale linear program (LP). The decision variables are of three different type. There are yearly

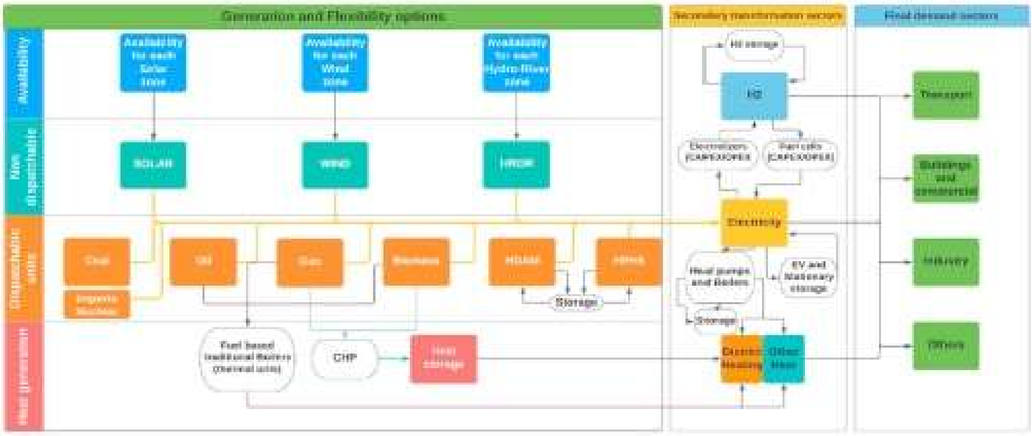


Fig. 1. Flowchart and connection within the H2RES model.

investment capacities that are made for each of the technologies at each year. The model assumes that the additional installed capacity is immediately available in the first hour of the year in which it is installed. The second type of decision variables are those representing the output of generators and storages (for each analysed sector) that are optimized for each hour of each simulated year for all technologies that have an installed capacity different than zero. The third set of variables corresponds to storage levels (hydro, heat, H_2) that, as for the dispatching, are modelled for each technology with an hourly resolution for each year in the horizon.

The H2RES model objective is that of minimizing the total system cost considering both operation and investment in new capacity for all years in the horizon. Since H2RES is able to simulate long-term planning, the future value of future operation and capacity costs are also actualized to the same year in order to enable a fair comparison between investment within such a large timeframe (e.g. from 2020 to 2050). Equation (1) shows the most generic expression of the H2RES objective.

$$\sum_{y}\sum_{p}\sum_{t} df_y\left[C_{t,p,y}D_{t,p,y} + C_{t,y}K_t Inv_{t,y} + R_{t,p,y}Ramp_{t,p,y} + I_{p,y}Imp_{p,y} + CO_2Price_y CO_2Levels_{t,p,y}\right] \quad (1)$$

In Equation (1), the different terms represent the dispatching cost ($D_{t,p,y}$) of each technology t, in hour p, in year y. The variable cost ($C_{t,p,y}$) depends on all operational costs both depending on fuels and those simply due to normal operation (i.e. non-fuel costs), as shown in Equation (2). This structure allows to simulate cost structures of different types of technologies.

$$C_{t,p,y} = \left[\frac{FuelCost_{t,p,y}}{eff_{t,p,y}} + NonFuelCost_{t,p,y}\right] \quad (2)$$

The investment cost is represented by the second term of Equation (1) in terms of cost of additional capacity for each technology, this is then annualised thanks to factor K_t where the subscript t indicates the technology. The term $C_{t,y}$ represents the capital cost of a certain technology that might change in the different modelled years so to model the technology change in cost (learning curve) of a technology that might have reduced capital cost in the future, this is an input. The cost for ramp up and down and for imports are represented by the third and fourth terms of Equation (1), respectively. It is worth specifying that the adopted version of H2RES allows only for electricity import and not for export. Furthermore, this is done having the import price as an input set by the users that is expressed with an hourly resolution for each of the modelled years. Furthermore, also the cost of emissions (i.e. CO_2 emissions) are taken into account (i.e. EUR/tCO_2).

Thus, H2RES evaluate the optimal size of different technologies as well as their operation schedule in terms of dispatching with the objective of minimizing the overall system cost. All of this, is subject to a set of technical and economic constraints. The core constraints and H2RES working principle are briefly explained in this section, for a more detailed description one can refer to Ref. [45] and to the open-source code that is available on H2RES website [46].

H2RES is able to disaggregate each type of demand (e.g. electricity, heat, and H_2) within the different sectors (i.e. industry, agriculture, and others). The core constraints are those that guarantee for each energy carrier that the required quantity is supplied in every hour of every year.

In order to supply such demands, generators output are optimized every hour of every year. The output level of every technology is of course constrained by the installed capacity that is settled at the beginning of each year considering new investment and the decommissioning period. Indeed, if capacity investment is allowed, the upper bound can be adjusted in future periods adding new capacity but always considering the maximum levels of allowed investments for technologies (potential of each technology). If required, a minimum level can also be set for certain technologies so as to analyse specific policy measures.

For storage technologies, H2RES optimize the state of charge at an hourly resolution for each year in the model horizon. Hydro-dam units are the only storage technologies with a "natural" input level depending on the inflows, while all other storage technologies' inputs is optimized by the model; this is the case heat storages, H_2 storages as well as batteries or other electricity storing technologies. Each storage unit has a minimum and a maximum state of charge that must be guaranteed for each hour in the time horizon. The state of charge also limits the dispatching capability in each hour.

The decision variables are optimized also under some policy constraints. Indeed, H2RES considers three main different policy dimensions, which can be used independently or together. First, H2RES allows to define different levels of critical excess of electricity production (CEEP) allowed during a given year. If the model is used in a long-term planning scenario, users can set a maximum CEEP level for each year in the time horizon. Secondly, H2RES considers targets for renewable energy in the form of RES share (%). As in the case of the CEEP target, H2RES allows to model different targets for different years in the model horizon. Hence, the model allows to analyse systems configurations that comply with a transition towards low carbon economies. Lastly, H2RES also considers yearly limits for CO_2 (or CO_{2eq}) emissions levels. As several long-term energy planning models, given their complexity and detailed modelling of the hourly operation of the energy system, H2RES does have some limitations in terms of technical details for some technologies. Nevertheless, the ability to analyse energy systems with a hourly resolution, as well as its technology richness and the different energy demands and sectors that the model is able to analyse makes it a reliable model, as it is also proven in Ref. [44] where it is validated against the PLEXOS model, or in Ref. [45] where H2RES is used to analyse country level decarbonization pathways, or, in Ref. [47] where it is used to assess RES integration in District Heating and Cooling system in mild and Mediterranean climates, among others.

To increase the technical detail of the model, in addition to the traditional constraints found in long-term energy system models, new ones have been added in order to consider the stability issues that are particularly relevant in the context of a small island. Being the model a "steady state" model with perfect foresight, the reserves are never actually necessary. What is checked in the model is that plants are ready to provide reserve but it does not consider the actual provision of reserve, but rather the implications of having sufficient reserve at hand. Obviously, the actual activation of a reserve would cause a deviation of the electricity generation in this steady state, e.g. to compensate an outage.

The general reserve constraint is shown in equations (3) and (4) for upwards and downwards reserves (both primary and secondary), respectively:

$$\sum_{t} r_{y,h,t}^{up\_TP} + \sum_{t} r_{y,h,t}^{up\_STO} + \sum_{t} r_{y,h,t}^{up\_HC} + \sum_{t} r_{y,h,t}^{up\_ELY} + \sum_{t} r_{y,h,t}^{up\_HP} \geq R_{y,h}^{up} \quad (3)$$

$$\sum_{t} r_{y,i,t}^{down\_TP} + \sum_{t} r_{y,i,t}^{down\_STO} + \sum_{t} r_{y,i,t}^{down\_FC} + \sum_{t} r_{y,i,t}^{down\_ELY} + \sum_{t} r_{y,i,t}^{down\_HP} \geq R_{y,i}^{down} \quad (4)$$

where, r indicated the available reserve offered by single plants and R is the reserve requirement to ensure the grid stability in every hour of every year. The superscripts have two information.

The first one can be *up* or *down* and it indicates if the reserve is meant for upwards or downwards reserves. The second part of the superscript indicates the technology (i.e. *TP* stands for Traditional Plants, *STO* for storage, and the other acronyms are the same used in the rest of the paper). The subscripts are three; the y and the i indicate that the constraints is checked in every hour of every year while t stands for the different plants belonging to the same technology group.

Equations from (5) to (16) shows the constraints for primary and secondary reserves (primary and secondary reserves is indicated by the subscript *1* or *2*, respectively).

$$r_{1,i,t}^{up\_TP} = \min\{Pmax_t - Pg_{i,t} \,;\, Pg_{i,t} \,;\, RampUp_t\} \quad (5)$$

$$r_{1,i,t}^{down\_TP} = \min\{Pg_{i,t} - Pmin_t \,;\, Pg_{i,t} \,;\, RampDown_t\} \quad (6)$$

$$r_{1,i,t}^{up\_STOout} = \min\{Pmax_t - Pout_{i,t} \,;\, Bat_{SOC\,i,t}\} \quad (7)$$

$$r_{1,i,t}^{up\_STOin} = Pin_{i,t} \quad (8)$$

$$r_{1,i,t}^{down\_STOout} = Pout_{i,t} \quad (9)$$

$$r_{1,i,t}^{down\_STOin} = \min\{Pmax_t - Pin_{i,t} \,;\, Bat_{SOCmax\,t} - Bat_{SOC\,i,t}\} \quad (10)$$

$$r_{2,i,t}^{up\_TP} = \min\{Pmax_t - Pg_{i,t} - r_{1,i,t}^{up\_TP} \,;\, RampUp_t\} \quad (11)$$

$$r_{2,i,t}^{down\_TP} = \min\{Pg_{i,t} - r_{1,i,t}^{down\_TP} - Pmin_t \,;\, RampDown_t\} \quad (12)$$

$$r_{2,i,t}^{up\_STOout} = \min\left\{Pmax_t - Pout_{i,t} - r_{1,i,t}^{up\_STOout} \,;\, Bat_{SOC\,i,t}\right\} \quad (13)$$

$$r_{2,i,t}^{up\_STOin} = Pin_{i,t} - r_{1,i,t}^{up\_STOin} \quad (14)$$

$$r_{2,i,t}^{down\_STOout} = Pout_{i,t} - r_{1,i,t}^{down\_STOout} \quad (15)$$

$$r_{2,i,t}^{down\_STOin} = \min\left\{Pmax_t - Pin_{i,t} - r_{1,i,t}^{down\_STOin} \,;\, Bat_{SOCmax\,t} - Bat_{SOC\,i,t}\right\} \quad (16)$$

The shown equation have been linearised in order to keep the model a LP one.

The reserve requirement was instead the sum of a percentage of the renewable, non-dispatchable, production (i.e. 20%) and of the electricity load (10%) in every hour. These values have been increased compared to the ones adopted in Ref. [48] since the island nature of the grid requires higher reserves.

In this research different scenarios will be analysed.

The scenarios will study the energy system with a growing renewable energy share up to 100% in 2050. This scenario will be analysed in 3 different cases:

1. Without ancillary reserves;
2. With primary reserves;
3. With primary and secondary reserves.

The scenarios will be analysed separately and then compared to understand the full impact of reserves when planning the energy transition.

3. Case study: Favignana island

The case study that has been analysed in this paper is that of the Favignana island within the Aegadian archipelago in the north-west coast of Sicily. Favignana is the biggest island of the archipelago with its 3407 inhabitants. As most of small islands around the world and in Italy, Favignana electricity demand of 12.56 GWh/y are supplied in almost its entirety by seven diesel generators with an overall nominal power of 12 MW. Additionally, on the island also a small production from rooftop PV systems can also be recorded (i.e. 170 kW_p).

Regarding other energy consumptions, transportation represents around 60% of the whole energy demand and this is mainly connected to maritime transportation that consumes 57.23 GWh/y. This is not unexpected since ferries are needed both for the connection with the mainland, with a consistent number of daily travellers for work and educational purposes, and between islands within the archipelago [49]. As for all demands, also the one for transport is highly seasonal due to the importance of tourism for the island. Terrestrial transportation is divided into diesel and gasoline and it is equal to 3.8 GWh/y and 5.5 GWh/y, respectively.

Most of the heating consumption is supposed to be provided by electricity and it is thus considered within the electricity consumption that has been provided by the island only DSO, SEA S.p.a.. Additionally, 3.4 GWh/y of LPG are also used for heating purposes.

The primary energy consumption share of each energy consuming sector can be seen in Fig. 2.

As previously briefly introduced, the island is a famous touristic destination this makes all the consumptions trends strongly seasonal with higher peak in summer as it can be seen for the electricity consumption in Fig. 3a. In Fig. 3b, statistics about the heating demand are depicted.

Regarding the local RES potential, their hourly profiles have been downloaded by renewablesninja [50].

All the technology-related data used in the analysis is described in Table 1. Availability factors of PV systems and wind are considered to remain similar to 2020 levels for each future year.

In Table 2, the cost of fossil fuels in the baseline year (i.e. 2020) are shown. It has been assumed a 1% increase rate per year for all fuel prices (i.e. gas, oil, biomass).

As regards Table 2, the higher cost has been considered due to logistic issues of insularity as evaluated and detailly explained in Ref. [57], the overprice is considered to be equal to 20% of the original cost on the mainland.

Regarding the optimisation variables upper thresholds have been estimated with the following hypothesis.

The upper bound for the total residential PV capacity has been identified to be equal to 18 MW_p as described in detail in Ref. [58]. Regarding large scale PV, the maximum capacity that can be installed

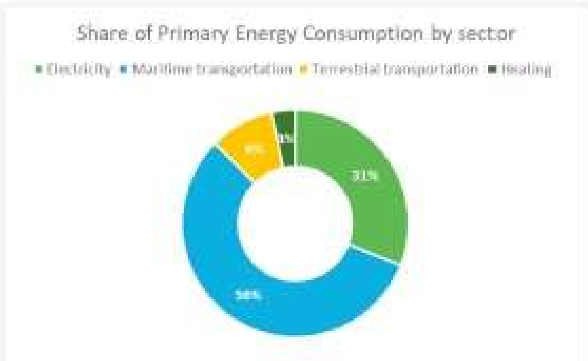
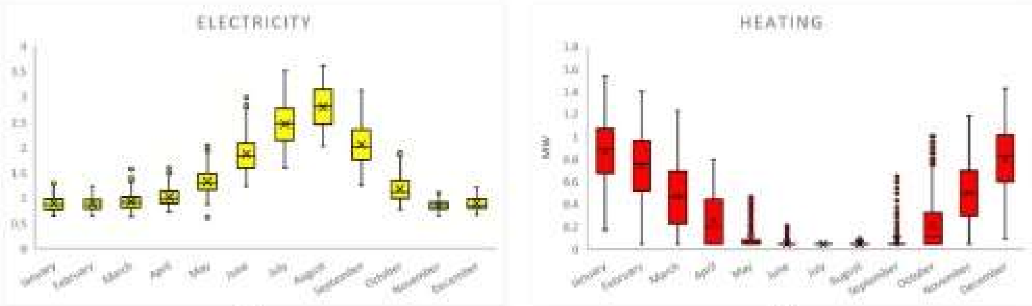


Fig. 2. Primary energy consumption share per sector.



a) b)

Fig. 3. Favignana a) electricity and b) heating loads.

Table 1
Techno-economic data for analysed technologies.

Technology	Units	INV 2020 (M€/unit)	INV 2030 (M€/unit)	INV 2040 (M€/unit)	INV 2050 (M€/unit)	Efficiency	Source
Large scale PV	MW	0.53	0.38	0.33	0.3	–	[51]
		0.83	0.69	–	0.56	–	[52]
Residential PV	MW	1.13	0.87	–	0.59	–	[51]
		1.25	1	–	0.85	–	[52]
Wind	MW	1.12	1.04	0.98	0.96	–	[51]
PEMFC CHP	MW	1.3	1.1	–	0.8	50%	[51]
SOFC CHP	MW	3.3	2	–	0.8	60%	[51]
Alkaline Electrolyzer	MW	0.65	0.45	0.3	0.25	66.5–78%	[53]
SOEC Electrolyzer	MW	4.5	1.9	1.3	0.78	77–83.5%	[53]
PEM Electrolyzer	MW	0.92	0.65	0.45	0.4	58–70.5%	[53]
H2 storage (tanks)	MWh	0.057	0.045	0.027	0.021	–	[54]
Li-ion Battery	MWh	1.042	0.622	0.394	0.255	92% (charge/discharge average)	[54]
biomass boiler	MWth	0.47	0.447	0.425	0.404	79–85%	[55]
gas boiler	MWth	0.278	0.265	0.252	0.24	99%	[55]
air-to-water HPs	MWth	1.2	1.076	1.016	0.956	3.282 (average)	[55]
geothermal HP	MWth	1.932	1.836	1.74	1.566	4.621 (average)	[55]
Electric boilers	MWth	0.89	0.85	0.81	0.77	100%	[55]

Table 2
Fuel cost [56].

Fuel	Cost [€/GJ]	Increased cost [€/GJ]
Natural gas	8.3	9.96
Diesel	16	19.2
Biodiesel	26.56	31.87
Gasoline	16.4	19.7

has been set to 2 MW as per communication from Favignana Municipality itself that has already identified the needed space on the island in accordance with the superintendence.

As regards batteries, the upper threshold has been identified based on the PV capacity upper bound thus hypothesizing a reasonable size that has been assumed as 100 MWh. As it can be seen in the results section, this upper bound does not impact the results since far lower sizes of Li-ion batteries are installed in all scenarios.

4. Results and discussion

In this section the results of the analysed scenarios are shown. In Fig. 4, large differences can be found in the energy produced every year from different energy vectors when reserves constraints are considered.

A gradual shift from solar and wind towards biomass produced electricity can be clearly seen. This is also mirrored by the investments in RES generators that indeed are affected by the constraints on primary and secondary reserves as shown in Figs. 5 and 6.

Indeed, it is visible how less consistent the investment in PV and Wind turbine are. This is due to three major reasons:

- the capacity of biomass generator to produce clean electricity
- the ability of biomass generators to provide primary and secondary reserves
- reduce the need of reserves ($R^{up}_{y,t}$ and $R^{down}_{y,t}$ in Equations (3) and (4)) by reducing the non-dispatchable electricity production

The lower non-dispatchable energy production also causes lower investment in Li-ion batteries as it can be seen in Fig. 6.

Regarding other flexible technologies, differences can be found for HPs and EBs as well as for FCs and ELYs as shown in Figs. 7 and 8. It must be noted that the adopted scales are different and HPs and EBs are in the scales of kilo-Watts while FCs and ELYs are in the scales of hundreds of kilo-Watts.

The installed capacity of all these four technologies is increased when primary reserves are needed compared to the case when no reserves are needed. Nevertheless, it is interesting to notice that in the case of secondary reserves the installed capacity of FCs, ELYs, and also EBs (even though the difference is only ca. 3 kW) decreases while HPs are the only flexible technology that slightly increases when secondary reserves are also taken into account.

It is now interesting to understand how the different technology are adopted for providing reserves.

In Fig. 9, the amount of reserves provided by each technology per year is shown both for upward reserves (Fig. 9a) and downwards one (Fig. 9b).

It is visible how the major sources of reserves in the baseline year are the two diesel generators and the small Li-ion plant. In the next years, biomass becomes the major reserve supplier, both up- and downwards followed by Li-ion batteries that in 2050, when a 100% RES share is

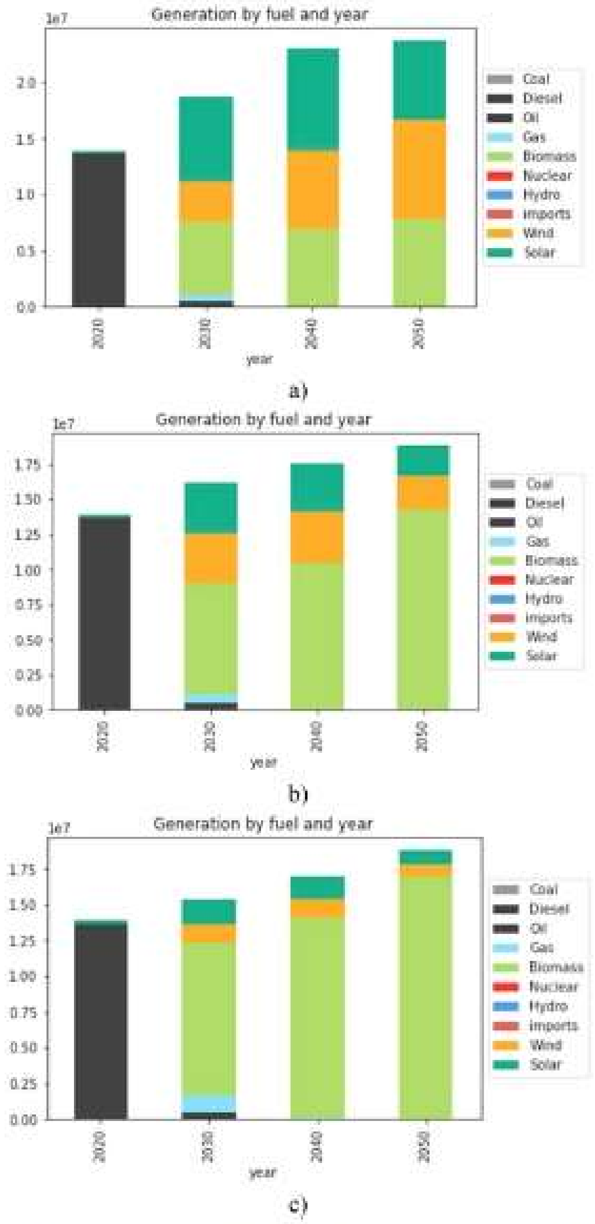


Fig. 4. Yearly energy production by energy carrier in scenarios a) without reserves, b) with primary reserves and c) with primary and secondary reserves.

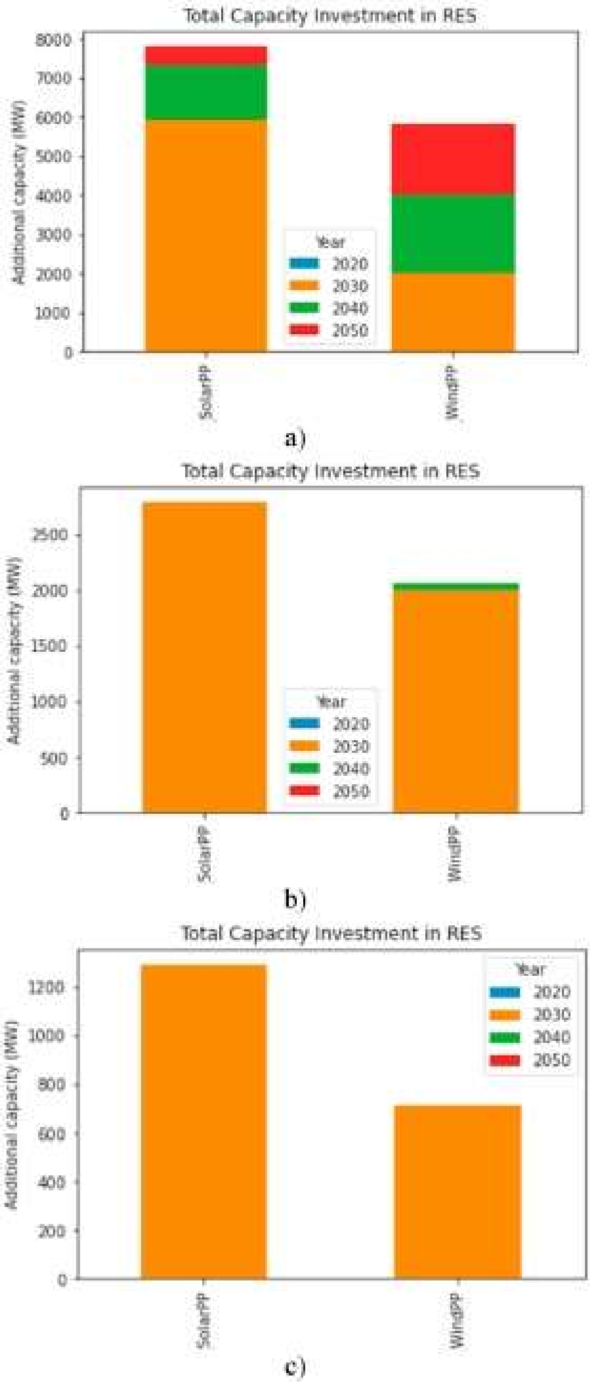


Fig. 5. Capacity investment per RES technology in scenarios a) without reserves, b) with primary reserves and c) with primary and secondary reserves.

reached, supply a comparable amount of reserves around the 800 MW in the whole year. Furthermore, when the 100% RES share is reached the need for ELY to provide downwards reserves is evident. It is worth noticing that a negligible amount of downward reserve is provided by EBs in 2050.

In Fig. 10, it can be appreciated how the different technologies are used in terms of electricity supply and reserve provision (in the case of Li-ion storage both charge and discharge are depicted).

It is interesting to analyse the different roles of technologies in the future energy system and how it changes throughout the years. Biomass is mainly used for electricity production with a minor contribution towards reserves in terms of time even though we know, from Fig. 9, that it is the biggest reserve provider of the whole energy system. The gas generator use instead shifts from being majorly adopted as electricity supplier towards being mainly a reserve provider in 2030 to then disappear in a 100% RES share system. In 2050, when the 100% RES share target is reached, hydrogen technologies are installed but they are used extremely differently. Indeed, the electrolyser's main function is that of a reserve provider and mainly for downwards reserve; while the

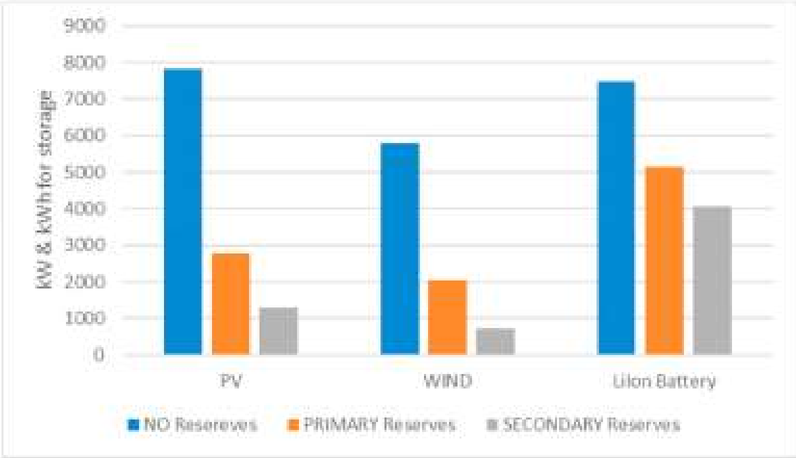


Fig. 6. Total PV, Wind Turbine and Li-ion battery storage installed power for a 100% RES share in different scenarios.

Fig. 7. Total Heat Pumps and Electric Boilers installed power for a 100% RES share in different scenarios.

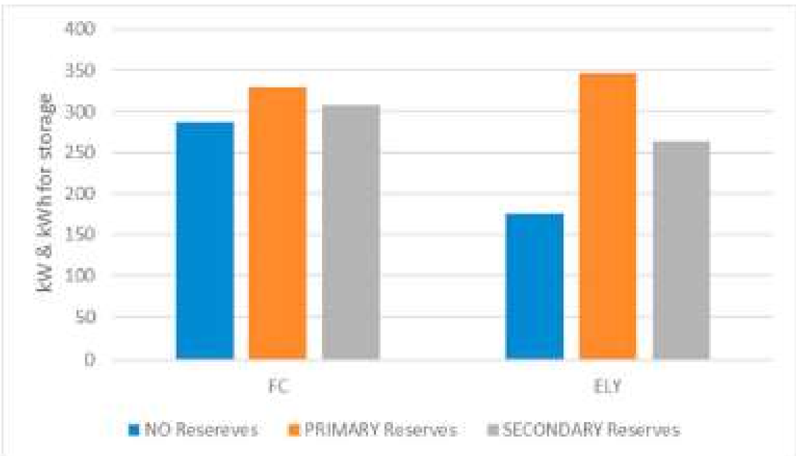


Fig. 8. Total Fuel Cells and Electrolysers installed capacity for a 100% RES share in different scenarios.

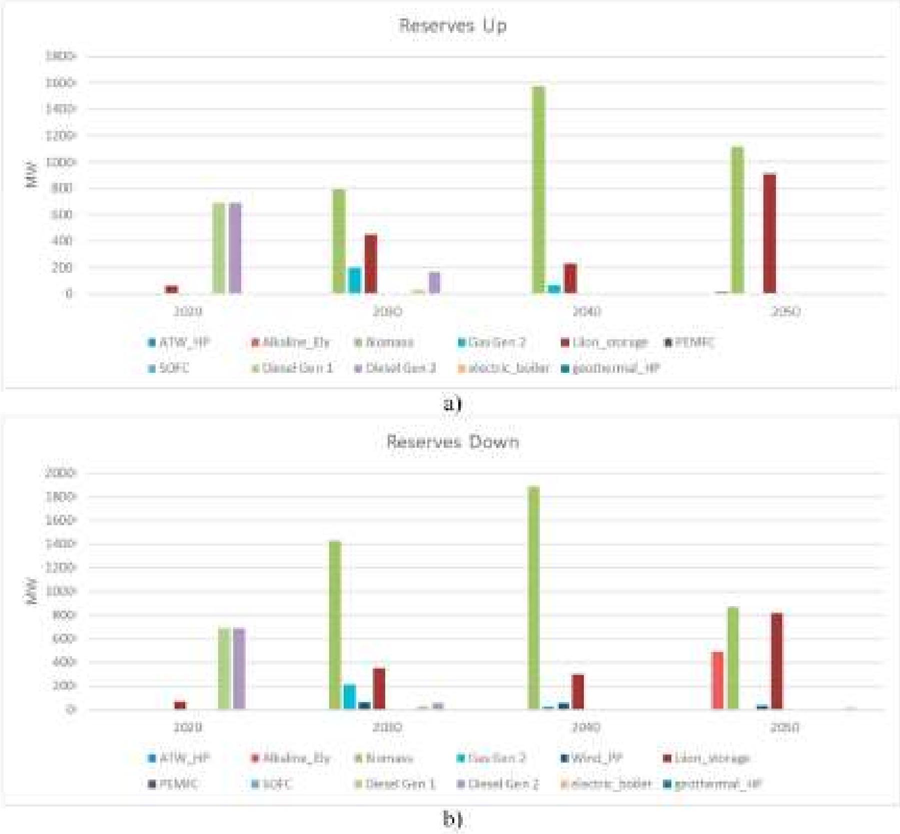


Fig. 9. Amount of Primary Reserves UP (a) and DOWN (b) supplied per technology per year.

FC, precisely a SOFC, is mainly used as a power generator while also providing both up and down reserve services. These outcomes provide interesting insights since they suggest that reserve provision might represent the core business model for ELYs while the use of hydrogen for power production through FCs would be almost negligible since it covers only around 10% of the time of use.

Li-ion batteries have a similar use throughout the whole time-horizon being mainly a reserve supplier with a balanced share of up- and down-wards reserve use. They also have a relevant role as a load (charge mode) and a power supplier (discharge) but only in 2020 when the RES share is fairly low and the need for reserves is limited. From 2030 onwards, when PV and Wind turbines are installed, Li-ion batteries work for almost 85% of the time as reserve providers.

Regarding the heating sector technologies, HPs and EBs have different roles in the system. HPs are installed in 2030 and are used for both heating supply and downwards reserves and this type of use is replicated also in the following years with an increase in the heating supply since the gas boilers that are initially installed are decommissioned and thus substituted by HPs. Differently than HPs, EBs are installed only in 2050 and are used almost entirely for downwards reserves.

5. Conclusion

The first conclusion that can be drawn is that when reserves are considered great differences in the optimal investment towards 100% RES share can be found.

Biomass generators become the best option for power production and so investments in PV and Wind turbines drop drastically. Indeed, biomass generators being dispatchable bring a threefold advantage such as i) providing clean energy, ii) being able to provide reserves services and iii) reduce the need for reserves that is evaluated as a percentage of the non-dispatchable power generation and of the power load.

Furthermore, Li-ion batteries are the second most provider of reserves services reaching a value that is comparable to the one provided by biomass generators in 2050.

It was also concluded that the hydrogen supply chain is advantageous only in a 100% RES share system (i.e. 2050) when both ELY and FC are installed. It is interesting though how differently these technologies are used. Indeed, ELY are used for most of the time as downwards reserves providers and only 10% of the time as a load to produce hydrogen. On the other hand, FCs are mostly used for power production (i.e. ca 60% of the time) but also for reserves provision with a balanced share between down and upwards reserves. This outcome can be interesting for rethinking the business model of ELYs but also for policy makers that should carefully think about proper markets for ancillary services. It should be noticed that in this paper the opportunity to export hydrogen was not considered, so the hydrogen price on the global and/or local markets might change the optimal operation strategy for such technology and mainly ELY.

It is nevertheless clear that at least primary reserves should be considered at planning stage in order to properly size not only the RES generators but more importantly all those technologies that will have to cope with the unpredictability of non-dispatchable RES.

It must be mentioned that like other long-term energy planning models, H2RES does have some limitations due to the assumptions made in terms of technical details since the model aims at analysing strategic long-term decisions.

Fig. 10. Percentage of type of use for main reserve provider technologies: a) Biomass generator; b) Gas generator; c) Li-ion battery; d) Wind turbine; e) Electrolyser; f) Solid-Oxide Fuel Cell; g) Heat Pumps; h) Electric Boilers.

Credit author statement

Daniele Groppi: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Visualization, Writing- Reviewing and Editing, Funding. **Felipe Feijoo:** Conceptualization, Methodology, Software, Visualization, Writing- Reviewing and Editing. **Antun Pfeifer:** Conceptualization, Investigation, Writing- Reviewing and Editing. **Davide Astiaso Garcia:** Supervision, Investigation, Writing- Reviewing and Editing, Writing- Reviewing and Editing. **Neven Duic:** Supervision, Investigation, Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All of the used data are obtained by public sources that have been duly cited in the research. Some data, i.e. the electricity consumption, has been provided by the DSO and cannot be shared.

Acknowledgements

This work was developed within the project "Modello di ottimizzazione per la pianificazione energetica a livello nazionale e analisi del vettore idrogeno" (Numero protocollo: AR22117A8683A3E5) supported by Sapienza University of Rome through the "Bando di Ateneo per la Ricerca 2022 – Avvio alla Ricerca" call for proposal. Co-authors (Antun Pfeifer, Neven Duić) are supported by the IP-2019-04-9482 "Istrazivanje puteva energetske tranzicije - meduovisnost "power-to-X" tehnologija, tehnologija odgovora potrosnje i povezivanja trzista energijom" INTERENERGY project, funded by the Croatian Science Foundation (Hrvatska Zaklada za Znanost). Felipe Feijoo was supported by the ANID - FONDECYT regular grant 1221894.

References

[1] Zhao ZY, Hao YX, Chang RD, Wang QC. Assessing the vulnerability of energy supply chains: influencing factors and countermeasures. Sustain Energy Technol Assessments 2023:56. https://doi.org/10.1016/j.seta.2023.103018.

[2] Mahmoudan A, Samadof P, Hosseinzadeh S, Astiaso Garcia D. A multigeneration cascade system using ground-source energy with cold recovery: 3E analyses and multi-objective optimization. Energy 2021;233. https://doi.org/10.1016/j.energy.2021.121185.

[3] IEA. Electricity market report - July. 2021. Paris: IEA; 2021 (last accessed January 2023), https://www.iea.org/reports/electricity-market-report-july-2021.

[4] Rodrigues R, Pietzcker R, Fragkos P, Price J, McDowall W, Siskos P, et al. Narrative-driven alternative roads to achieve mid-century CO2 net neutrality in europe. Energy 2022;239. https://doi.org/10.1016/j.energy.2021.121908.

[5] IEA. World energy outlook 2021. Link. Paris: IEA; 2021 (last access January 2023), https://www.iea.org/reports/world-energy-outlook-2021.

[6] IEA. Gas market report, Q4 2021. Link. Paris: IEA; 2021 (last access January 2023), https://www.iea.org/reports/gas-market-report-q4-2021.

[7] IEA. Coal 2021. Link. Paris: IEA; 2021 (last access January 2023), https://www.iea.org/reports/coal-2021.

[8] Sarasa C, Turner K. Can a combination of efficiency initiatives give us "good" rebound effects? Energy 2021;235. https://doi.org/10.1016/j.energy.2021.121335.

[9] IEA. Energy technology perspectives 2023. Paris: IEA; 2023. License: CC BY 4.0, https://www.iea.org/reports/energy-technology-perspectives-2023.

[10] Andreu JF, Schneider DR, Krajačić G. Evaluation of integration of solar energy into the district heating system of the city of Velika Gorica. Therm Sci 2016;20: 1049–60.

[11] Bertheau P. Supplying not electrified islands with 100% renewable energy based micro grids: a geospatial and techno-economic analysis for the Philippines. Energy 2020:202. https://doi.org/10.1016/j.energy.2020.117670.

[12] Moretti M, Djomo SN, Azadi H, May K, De Vos K, Van Passel S, et al. A systematic review of environmental and economic impacts of smart grids. Renew Sustain Energy Rev 2017;68:888–98.

[13] Mimica M, Krajačić G. The smart islands method for defining energy planning scenarios on islands. Energy 2021;237. https://doi.org/10.1016/j.energy.2021.121653.

[14] Beccali M, Finocchiaro P, Ippolito MG, Leone G, Panno D, Zizzo G. Analysis of some renewable energy uses and demand side measures for hotels on small mediterranean islands: a case study. Energy 2018;157:106–14. https://doi.org/10.1016/j.energy.2018.05.130.

[15] O'Connell S, Reynders G, Keane MM. Impact of source variability on flexibility for demand response. Energy 2021;237. https://doi.org/10.1016/j.energy.2021.121612.

[16] Ministero dello Sviluppo Economico. Ministerial decree - renewable energy sources in small islands not connected to the mainland. Fonti Rinnovabili Nelle Isole Minori Non Interconnesse; 2017.

[17] Kirkerud JG, Nagel NO, Bolkesjø TF. The role of demand response in the future renewable northern european energy system. Energy 2021;235. https://doi.org/10.1016/j.energy.2021.121336.

[18] Hrnčić B, Pfeifer A, Jurić F, Duić N, Ivanović V, Vušanović I. Different investment dynamics in energy transition towards a 100% renewable energy system. Energy 2021;237. https://doi.org/10.1016/j.energy.2021.121526.

[19] Capone M, Guelpa E, Mancò G, Verda V. Integration of storage and thermal demand response to unlock flexibility in district multi-energy systems. Energy 2021;237. https://doi.org/10.1016/j.energy.2021.121601.

[20] Bellocchi S, Manno M, Noussan M, Prina MG, Vellini M. Electrification of transport and residential heating sectors in support of renewable penetration: scenarios for the Italian energy system. Energy 2020;196. https://doi.org/10.1016/j.energy.2020.117062.

[21] Testi D, Urbanucci L, Giola C, Schito E, Conti P. Stochastic optimal integration of decentralized heat pumps in a smart thermal and electric micro-grid. Energy Convers Manag 2020:210. https://doi.org/10.1016/j.enconman.2020.112734.

[22] Dranka GG, Ferreira P, Vaz AIF. Integrating supply and demand-side management in renewable-based energy systems. Energy 2021:232. https://doi.org/10.1016/j.energy.2021.120978.

[23] Li C, Chen D, Li Y, Li F, Li R, Wu Q, et al. Exploring the interaction between renewables and energy storage for zero-carbon electricity systems. Energy 2022: 261. https://doi.org/10.1016/j.energy.2022.125247.

[24] Yuan M, Thellufsen JZ, Lund H, Liang Y. The electrification of transportation in energy transition. Energy 2021:236. https://doi.org/10.1016/j.energy.2021.121564.

[25] Huckebrink D, Bertsch V. Decarbonising the residential heating sector: a techno-economic assessment of selected technologies. Energy 2022:257. https://doi.org/10.1016/j.energy.2022.124605.

[26] Angelidis O, Ioannou A, Friedrich D, Thomson A, Falcone G. District heating and cooling networks with decentralised energy substations: opportunities and barriers for holistic energy system decarbonisation. Energy 2023:269. https://doi.org/10.1016/j.energy.2023.126740.

[27] Schmid F, Behrendt F. Genetic sizing optimization of residential multi-carrier energy systems: the aim of energy autarky and its cost. Energy 2023:262. https://doi.org/10.1016/j.energy.2022.125421.

[28] Song S, Li T, Liu P, Li Z. The transition pathway of energy supply systems towards carbon neutrality based on a multi-regional energy infrastructure planning approach: a case study of China. Energy 2022:238. https://doi.org/10.1016/j.energy.2021.122037.

[29] Kan X, Reichenberg L, Hedenus F. The impacts of the electricity demand pattern on electricity system cost and the electricity supply mix: a comprehensive modeling analysis for europe. Energy 2021:235. https://doi.org/10.1016/j.energy.2021.121329.

[30] Koščak Kolin S, Karasalihović Sedlar D, Kurevija T. Relationship between electricity and economic growth for long-term periods: new possibilities for energy prediction. Energy 2021;228. https://doi.org/10.1016/j.energy.2021.120539.

[31] Brijs T, van Stiphout A, Siddiqui S, Belmans R. Evaluating the role of electricity storage by considering short-term operation in long-term planning. Sustain Energy, Grids Networks 2017;10:104–17. https://doi.org/10.1016/j.segan.2017.04.002.

[32] Van Stiphout A, De Vos K, Deconinck G. The impact of operating reserves on investment planning of renewable power systems. IEEE Trans Power Syst 2016;32 (1):378–88. https://doi.org/10.1109/TPWRS.2016.2565058.

[33] Palmintier B. Flexibility in generation planning: identifying key operating constraints. Power systems computation conference (PSCC). IEEE 2014:1–7. 2014.

[34] Poncelet K. Long-term energy-system optimization models: capturing the challenges of integrating intermittent renewable energy sources and assessing the suitability for descriptive scenario analyses [Ph.D. thesis]. KU Leuven; 2018. URL, https://lirias.kuleuven.be/bitstream/123456789/604991/1/thesis_final.pdf.

[35] Palmintier BS, Webster MD. Impact of operational flexibility on electricity generation planning with renewable and carbon targets. IEEE Trans Sustain Energy 2016;7(2):672–84. https://doi.org/10.1109/TSTE.2015.2498640.

[36] Palmintier B, Webster M. Impact of unit commitment constraints on generation expansion planning with renewables. In: 2011 IEEE power and energy society general meeting; 2011. p. 1–7. https://doi.org/10.1109/PES.2011.6038963.

[37] Hua B, Baldick R, Wang J. Representing operational flexibility in generation expansion planning through convex relaxation of unit commitment. IEEE Trans Power Syst 2018;33(2):2272–81. https://doi.org/10.1109/TPWRS.2017.2735026.

[38] Nogales A, Wogrin S, Centeno E. Impact of technical operational details on generation expansion in oligopolistic power markets. IET Gener Transm Distrib 2016;10(9):2118–26. https://doi.org/10.1049/iet-gtd.2015.1148.

[39] Poncelet K, Delarue E, D'haeseleer W. Unit commitment constraints in long-term planning models: relevance, pitfalls and the role of assumptions on flexibility. Appl Energy 2020;258. https://doi.org/10.1016/j.apenergy.2019.113843.

[40] Pavić I, Capuder T, Kuzle I. Value of flexible electric vehicles in providing spinning reserve services. Appl Energy 2015;157:60–74. https://doi.org/10.1016/j.apenergy.2015.07.070.

[41] Pavić I, Capuder T, Kuzle I. Low carbon technologies as providers of operational flexibility in future power systems. Appl Energy 2016;168:724–38. https://doi.org/10.1016/j.apenergy.2016.01.123.

[42] Brown M, Cole W, Eurek K, Becker J, Bielen D, Chernyakhovskiy I, Cohen S, et al. Regional energy deployment system (ReEDS) model documentation: version 2019. Golden, CO: National Renewable Energy Laboratory; 2020. NREL/TP-6A20-74111, https://www.nrel.gov/docs/fy20osti/74111.pdf.

[43] link H2RES official website. 2023. last access January, https://h2res.org/.

[44] Herc L, Pfeifer A, Feijoo F, Duic N. Energy system transitions pathways with the new H2RES model: a comparison with existing planning tool. E-Prime – Adv Electric Eng, Electron Energy 2021;1. https://doi.org/10.1016/j.prime.2021.100024.

[45] Feijoo F, Pfeifer A, Herk L, Groppi D, Duic N. A long-term capacity investment and operational energy planning model with power-to-X and flexibility technologies. Renew Sustain Energy Rev 2022;167. https://doi.org/10.1016/j.rser.2022.112781.

[46] Link Official website "H2RES - energy system modelling software". 2023. Last access January, https://h2res.org/.

[47] Novosel T, Feijoo F, Duić N, Domac J. Impact of district heating and cooling on the potential for the integration of variable renewable energy sources in mild and

mediterranean climates. Energy Convers Manag 2022;272. https://doi.org/10.1016/j.enconman.2022.116374.

[48] Cole W, Rurek K, Vincent N, Mai T, Mowers M, Brinkman G. Operating reserves in long-term planning models. 2018. NREL/PR-6A20-71148 June 1.

[49] Comune di Favignana n.d (last access January 2023), https://www.guida-favignana.it/news/favignana-approvato-piano-azione-energia-sostenibile-clima-2/.

[50] link Renewables Ninja website. 2023. last access January, https://www.renewables.ninja/.

[51] Technology data for generation of electricity and district heating | energistyrelsen. n.d. https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-generation-electricity-and; 2023. last accessed January

[52] Østergaard PA. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Appl Energy 2015;154:921–33. https://doi.org/10.1016/j.apenergy.2015.05.086.

[53] Technology data for renewable fuels | energistyrelsen n.d. last access January, https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-renewable-fuels; 2023.

[54] Technology data for energy storage | energistyrelsen n.d. https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-energy-storage; 2023. last access January.

[55] Technology data for individual heating plants | energistyrelsen n.d.. 2023. https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-individual-heating-plants. last access January.

[56] last access January EnergyPLAN website, downloadable cost database, link. 2023. https://www.energyplan.eu/useful_resources/costdatabase/.

[57] Groppi D, Astiaso Garcia D, Lo Basso G, De Santoli L. Synergy between smart energy systems simulation tools for greening small mediterranean islands. Renew Energy 2019;135:515–24. https://doi.org/10.1016/j.renene.2018.12.043.

[58] Pfeifer A, Bošković F, Dobravec V, Matak N, Krajačić G, Duić N, Pukšec T. Building smart energy systems on Croatian islands by increasing integration of renewable energy sources and electric vehicles. In: Paper presented at the Conference Proceedings - 2017 17th IEEE International Conference on Environment and Electrical Engineering and 2017 1st IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe; 2017. https://doi.org/10.1109/EEEIC.2017.7977401.